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Using PMU signals from dominant paths in power system wide-area damping control

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ABSTRACT

This article presents a comprehensive study of dominant inter-area oscillation path signals and their application for power system wide-area damping control (WADC). The analysis, carried out on both small and large study systems, focuses on the relationships that emerge from physical characteristics of inter-area oscillations, namely the modal observability of signals from dominant paths and their corresponding control loop system properties (i.e. stability and robustness). The aim is to be able to appropriately exploit the dominant path signals for the mitigation of inter-area oscillations. Guidelines and considerations are provided to facilitate the design of WADC using the proposed approach.

1. Introduction

Motivation

In response to a continual increase in electricity demand and the trend for more interconnections [1], power systems are driven closer to their physical operation limits, especially those of transmission capacity. Consequently, one critical issue concerning security and reliability of power system operation is the mitigation of inter-area oscillations. Various approaches for damping control design have been investigated in previous works [2–5]. Among different damping devices, power system stabilizers (PSS) are the most commonly used.

The advent of phasor measurement units (PMU) makes possible the use of remote or *wide-area* signals which enables various applications. Of significance is the wide-area damping control (WADC) application which utilizes remote measurements from PMUs to increase damping of the inter-area oscillations. It has been suggested that wide-area control can be more effective than local control [2,3,5] thanks to their larger observability of the inter-area modes. This makes the exploitation of PMU signals desirable for damping control purposes. One of the major challenges in WADC design is, however, the selection of feedback input signals. Which remote signal would give a satisfactory or the most effective damping performance?

Previous work

Among all available PMU signals,[1] [6] presents a systematic approach using the concept *dominant inter-area oscillation paths* to select feedback input signals having highest open-loop observability. The term *network modeshape*, a variable used to characterize the dominant path, has a commensurate relationship with damping effectiveness, i.e., the larger the network modeshape a signal has, the higher damping ratio the system can achieve. This relationship has been demonstrated in [7], where it has been shown that damping performance of a system corresponds to the network modeshape content of the selected feedback input.

Another challenge with WADC design is latency handling. Recently, many power system studies have considered fixed time delays where Padé approximation is used to represent them [8,9,3] whereas time-varying delays have also been investigated in several works including [10–12]. Regardless of their representation, deterministic or stochastic, time delays have detrimental impacts on system performance and can lead to loss of synchronism or instability [13]. As such, to implement PMU measurements

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[1] Voltage and current phasors, i.e., voltage and current magnitude and angles.

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for WADC, time delays, together with their impacts on control performance and system stability, must be carefully investigated.

The study in [14] presents preliminary studies on different properties of control systems using dominant path signals. The main finding is the trade-off between damping capacity and the maximum allowable delay the system can accommodate, i.e. delay margin. Relationship between delay margin and WADC parameters has been investigated in [12] where a method to compute delay margin is proposed. Since delay margin determines system stability, it can be used as a metric for WADC design.

Objectives

The objective of this article is twofold: (i) to provide a comprehensive analysis of the relationship between the *network modeshape* and different properties of control loop system (particularly, those related to damping performance, stability and robustness) using dominant inter-area oscillation path signals for WADC design, and (ii) to demonstrate and prove such relationships on a larger power network (since the studies [7,14] were carried out on a small-scale two-area system). With these findings, one can properly use signals from the dominant path in the design of controllers to effectively mitigate inter-area oscillations that constrain power transfer capacity and affect system stability.

Contributions

The contributions of this article are summarized as follows:

- Summary of important relationships (those that are related to stability and robustness) of control loops using dominant inter-area oscillation path signals as feedback inputs.
- Realization of the dominant inter-area oscillation path concept on a large power system.
- A metric and guideline for WADC design.

Paper organization

The paper is organized as follows. Section 2 introduces important concepts and summarizes major findings in preceding works by the authors. In Section 3, study system descriptions and case studies are described. Section 4 presents the main findings of this work, i.e., the relationships between control loop properties and network modeshape of the dominant path signals. Section 5 provides the verification of the designed controllers and delay margins through nonlinear time-domain simulations while in Section 6 the properties of a large system are demonstrated. Section 7 discusses some practical considerations and proposes some guidelines for WADC design while in Section 8, comparative analysis on different signal selection approaches are presented. Conclusions are presented in Section 9.

2. Basis of study

This section introduces important concepts used throughout the study and summarizes major findings in preceding works.

2.1. Important concepts

- *Interaction paths* are defined as the group of transmission lines, buses, and controllers which the generators in a system use for exchanging energy during swings [15].
- *Dominant inter-area oscillation paths* are defined as the interaction paths containing the highest content of the inter-area mode. They are pinpointed by network modeshape of signals on the dominant paths. These network modeshapes have certain features which are deterministic [6].
- *Network modeshapes (S)* are the projection of the network sensitivities (C) onto the modeshape (Φ) and are computed from the product of the two terms. They indicate how much of the content of each mode is distributed within the network variables. The network variables of interest are voltage phasors, i.e., voltage magnitude and angles. Thus, their corresponding network modeshapes are represented by S_V and S_θ, respectively. The mathematical expressions of the network modeshapes are provided below.

  Suppose the linearized model of an N-machine power system can be given in a state-space form as

$$\Delta\dot{x}_P = A_P\Delta x_P + B_P\Delta u_P \quad (1)$$

$$\Delta y_P = C_P\Delta x_P + D_P\Delta u_P, \quad (2)$$

  where A_P is the system matrix, B_P the input matrix, C_P the output matrix, D_P the feedforward matrix, x_P the state vector, u_P the control vector, and y_P the output vector.

  Assuming $u_P = 0$, the model is expressed as

$$\underbrace{\begin{bmatrix}\Delta\dot{\delta}\\ \Delta\dot{\omega}\\ \Delta\dot{z}\end{bmatrix}}_{\Delta\dot{x}} = \underbrace{\begin{bmatrix}A_{11} & A_{12} & A_{13}\\ A_{21} & A_{22} & A_{23}\\ A_{31} & A_{32} & A_{33}\end{bmatrix}}_{A}\underbrace{\begin{bmatrix}\Delta\delta\\ \Delta\omega\\ \Delta z\end{bmatrix}}_{\Delta x} \quad (3)$$

  where matrix A represents the state matrix corresponding to the state variables $\Delta\delta$, $\Delta\omega$, and Δz. Elements in z refer to other state variables. Then, performing eigenanalysis, the mode shape is derived from

$$A\Phi = \lambda\Phi \quad (4)$$

  where λ are eigenvalues of the system and $\Phi = [\Phi_1\Phi_2\cdots\Phi_n]$ are the corresponding right eigenvectors (or mode shapes) and n is the number of state variables. Inter-area oscillations, as well as other modes, are determined from the eigenvalues.

  The sensitivities of interest are the bus voltage phasors with respect to change in the state variables, e.g. machine's rotor angle (δ) or speed (ω). That is, the network sensitivities are the C_P matrix from Eq. (2) with voltage magnitude (V) and angle (θ) as the outputs, Δy.

  Sensitivities of the voltage magnitude (C_V) and angle (C_θ) are expressed as

$$l\underbrace{\begin{bmatrix}\Delta V\\ \Delta\theta\end{bmatrix}}_{\Delta y} = \underbrace{\begin{bmatrix}\frac{\partial V}{\partial\delta} & \frac{\partial V}{\partial\omega} & \frac{\partial V}{\partial z}\\ \frac{\partial\theta}{\partial\delta} & \frac{\partial\theta}{\partial\omega} & \frac{\partial\theta}{\partial z}\end{bmatrix}}_{C}\underbrace{\begin{bmatrix}\Delta\delta\\ \Delta\omega\\ \Delta z\end{bmatrix}}_{\Delta x} = \begin{bmatrix}C_V\\ C_\theta\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\\ \Delta z\end{bmatrix} \quad (5)$$

$$C_V = \begin{bmatrix}C_{V\delta} & C_{V\omega} & C_{Vz}\end{bmatrix},$$

$$C_\theta = \begin{bmatrix}C_{\theta\delta} & C_{\theta\omega} & C_{\theta z}\end{bmatrix}.$$

  Then, the expressions for voltage magnitude and angle modeshapes, S_V and S_θ, are

$$S_V = C_V\Phi, \qquad S_\theta = C_\theta\Phi. \quad (6)$$

- *Delay margin (DM)* is defined as the smallest time required to destabilize the closed-loop system [16]. It can be computed from the following. Fig. 1 shows a feedback connection of three systems: a plant $G(s)$, a controller $H(s)$, and a time delay $TD(s)$. The time delay is represented by a 2nd-order Padé approximation:

$$TD(s) \approx \frac{12 - 6sT_d + T_d^2s^2}{12 + 6sT_d + T_d^2s^2}, \quad (7)$$

  where T_d represents time delay in second.